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SUMMARY

An analysis of the orbit of the satellite Calsphere 1 confirms the large semi-annual variation in density at heights near 1100 km previously found from the orbit of Echo 2, and not predicted by present atmospheric models. This variation is probably due to relatively smaller variations at much lower altitudes, in particular variations at heights near 120 km, which is taken as the lower boundary for the construction of upper-atmosphere models.

Departmental Reference: Space 164

CONTENTS

1 INTRODUCTION

Values of air density in the lower exosphere have recently been evaluated[1] from the change in orbital period of the spherical satellite Echo 2 (1964-4A) for dates between February 1964 and December 1965. The possibility that Echo 2 experiences appreciable electric drag[2,3] cannot be entirely ruled out, but both induced electric drag and Alfvén wave drag should be insignificant for small satellites. The electric drag acting on Echo 2 has therefore been investigated by comparing its drag with that of Calsphere 1 (1964-63C), which is a polished aluminium sphere having a diameter of 0.36 m and a weight of 0.98 kg. Calsphere 1 and its companion, Calsphere 2 (1964-63E), which is of the same size but has a weight of 9.8 kg, were originally placed into orbit for use as standard radar targets[4]. The diameter of Echo 2 is 41 m and exceeds the diameter of the Calspheres by a factor of 114.

Values of air density obtained from Echo 2 were found to exhibit a pronounced semi-annual variation. In the present paper this effect is confirmed by the secular acceleration of Calsphere 1, and the source of this large variation is discussed.

2 ORBITAL DATA

Orbital data for 1964-63C are given in the form of 'five-card elements' by Spadats/Spacetrack; new values of these elements are issued whenever the predictions based on the previous set develop appreciable errors. At the time of writing, elements are available for dates between Modified Julian Day (MJD) 38785 and MJD 39218. Since the eccentricity is extremely small, varying between about 0.001 and 0.0025, values of air density can be found at the mean height, assuming a circular orbit, without introducing significant errors. The eccentricity also appears to be sufficiently small for the effect of solar radiation pressure on the orbital period to be negligible.

For a nearly circular orbit there can be an appreciable variation in anomalistic period due to the rapid motion of perigee. As with Echo 2, the corrected anomalistic period T is taken as

$$T = \frac{1}{\dot{\omega} + \dot{M}} ,$$

where ω is the argument of perigee and M the mean anomaly. The corrected secular acceleration is given by

$$\dot{T} = -\frac{\ddot{\omega} + \ddot{M}}{(\dot{\omega} + \dot{M})^2} .$$

Values of $\dot{\omega} + \dot{M}$ were obtained from the five-card elements by differencing consecutive values of $\omega + M$ and dividing by the time interval; the results are shown in Fig.1. The quantity $\dot{\omega} + \dot{M}$ varies very little, so that the secular acceleration is proportional to $\ddot{\omega} + \ddot{M}$.

3 VALUES OF DENSITY

The average air density experienced by a satellite in a circular orbit of radius a is related to the rate of change of orbital period $\dot{T}$ by[5]

$$\rho = -\frac{\dot{T}}{3\pi a \delta} ,$$

where $\delta = FSC_D/m$, S is the cross-sectional area, C_D the drag coefficient and m the mass of the satellite. F, the factor which allows for atmospheric rotation, is unity for Calsphere 1 since its orbital inclination is $89^\circ.9$. The molecular speed ratio is about 3.5, so that the drag coefficient[6] is unlikely to differ from 2.8 by more than about 10 per cent. We then have $\delta = 0.291$ m^2/kg.

During 1965 the mean rate of change of orbital period for Calsphere 1 was -1.80×10^{-8}, which gives a value of 8.83×10^{-19} g/cm^3 for the mean density at the mean height of 1080 km.

There is evidence in Fig.1 of a semi-annual variation in density, with a minimum in July-August and a maximum in October. The minimum value of $-\dot{T}$ occurs in July and is about 1.38×10^{-8}, giving a minimum density of 6.75×10^{-19} g/cm^3; the maximum value of $-\dot{T}$ occurs in October and is 2.23×10^{-8}, giving a maximum density of 10.9×10^{-19} g/cm^3. Unfortunately the data are too sparse to show variations in greater detail.

4 DISCUSSION

The mean and two extreme values of density obtained from Calsphere 1 are shown in Fig.2, together with the corresponding values of density at a height of 1130 km obtained[1] from Echo 2 for 1965. When the mean density from Calsphere 1 is adjusted to a height of 1130 km, it is found to be 13% lower than the corresponding value from Echo 2. It is to be expected that the mean density from Echo will show a slight bias towards the larger daytime value, since perigee never samples true night-time conditions. The agreement between the mean densities from these two satellites, whose diameters differ by a factor of 114, gives adequate confirmation that the electric drag acting on Echo 2 is not large; in fact,

the average value is unlikely to exceed about 10% of the neutral particle drag. The electric drag may, of course, exceed this value at certain points in the orbit, e.g. where the satellite's velocity vector is perpendicular to the Earth's magnetic field.

Echo 2 has indicated a pronounced semi-annual variation in density[1] at 1130 km. Although the magnitude of the effect is not so large in 1965 as in the previous year, the maximum density still exceeds the minimum by a factor of over 2. Calsphere 1 does not indicate such a large magnitude as found for Echo 2, the October maximum density exceeding the July minimum by a factor of only just over 1.6. However, the data for Calsphere 1 are neither sufficiently accurate nor sufficiently frequent to allow a good estimate of the maximum and minimum values of density. The values quoted in Section 3 may well be underestimates of the extremes.

Also shown in Fig.2 are values of density given by Jacchia's static diffusion models[7] for exospheric temperatures of 700 and 900°K; these values are representative of the extremes of the day-to-night variation for the solar conditions prevailing in 1965. The mean densities obtained from both Calsphere and Echo appear lower than might have been expected from extrapolation of the models. The reason for this is that the models are based on densities obtained using a constant drag coefficient of 2.2, whereas C_D increases with height and the densities from Echo 2 and Calsphere 1 were obtained using a drag coefficient of 2.8.

Jacchia[8] believes that the semi-annual effect is due to temperature variations in the thermosphere. On the basis of diffusion models[7], which are constructed from observational values of density at heights between 350 and 700 km, the semi-annual variation in density corresponds to a variation in exospheric temperature of about 75°K for the solar radiation flux which prevailed in 1965. For these conditions the models indicate that the magnitude of the semi-annual effect reaches a maximum of about 2 at heights near 500-600 km, and then decreases, so that the effect is almost non-existent at 1000 km. Since the observed change at heights near 1100 km is by a factor of about 2, it is evident that a temperature change of 75° is completely inadequate as an explanation.

There appear to be two possible causes for the discrepancy between the large observed magnitude of the semi-annual effect and the small magnitude predicted on the basis of diffusion models. First, there may be a further source of heating, in which case part of the effect might be due to the solar

wind, as originally suggested by Paetzold and Zschörner[9]. Some of the heat input could then arise from variations in the Earth-Sun distance and in the Earth's heliographic latitude. In this respect, it is worth noting that there is a pronounced minimum in July when the Earth is at its greatest distance from the Sun.

The second, and more likely explanation, is that atmospheric variations cannot be explained entirely on the basis of variations in temperature. The theoretical models probably underestimate the magnitude of the semi-annual effect in the exosphere because they are constructed assuming a fixed composition at a height of 120 km. To calculate the concentrations of neutral constituents in the upper atmosphere, it is necessary to choose an arbitrary level above which diffusive equilibrium is assumed. The exact base of the diffusion-controlled region is difficult to define, however, since there is a gradual transition from perfect turbulent mixing to molecular diffusion. It has recently been suggested[10] that the level separating the mixing-controlled and diffusion-controlled regions is best defined as the height at which the eddy and molecular diffusion coefficients are equal. This height, which has been termed the turbopause, differs for different constituents since their molecular diffusion coefficients are not the same. The rate of eddy mixing is normally the factor which controls the composition of the atmosphere in the transition region, and hence at all higher altitudes. A major constituent in the lower exosphere (500-1500 km) is helium, whose concentration is much more sensitive than other elements to the diffusion equilibrium level. According to Kockarts and Nicolet[11] a decrease of 5 km in the diffusion equilibrium level corresponds to an increase by a factor of about 2 in the helium concentration "dans l'hétérosphère supérieure", i.e. presumably at heights of 500 km and upwards. Helium has a long relaxation time, of order 2-4 weeks, so that for this constituent long-term variations are the ones most likely to be attributable to changes in the height of the turbopause. It is not unlikely that variations in this height accompany the semi-annual heating which occurs in the thermosphere.

It is worth noting that there have been other indications that the helium distribution is not adequately represented by diffusion models. Roemer[12] has found that densities obtained from Explorer 9 (1961 δ 1) would be in better agreement with Jacchia's static diffusion models if the helium concentration above 600 km was increased by 10 to 25%. Only a very small decrease in the height of the turbopause would be required to produce this effect.

From an analysis of the data obtained from the mass spectrometer experiment aboard Explorer 17 (1963-9A), at heights of 250 to 800 km, Reber and Nicolet[13] found large variations in the absolute concentrations of different species measured at the same altitudes and local times. For helium in particular, the variations are much too large to be due to changes in exospheric temperature

alone and must be attributed to changes in the boundary conditions at the height where diffusive equilibrium begins. As well as the possible variations of the height of this level, variations in all other atmospheric properties may be important. In particular, the density is now known[14] to be significantly greater in winter than in summer at 120 km, which is the height used as the base for the construction of upper-atmosphere models.

The daytime helium concentrations given in Fig.14 of Ref.13 are particularly interesting. If the differences in local times between the data points are borne in mind, there is a strong indication that near midday the helium concentration is higher in the southern hemisphere than in the northern. Since these measurements are for late May 1963, the helium concentration is high by day in the winter hemisphere. In the light of these results, a diurnal bulge in the winter hemisphere at heights between 550 and 750 km, as found by Keating and Prior[15], is not so surprising. At times of low solar activity helium is a major constituent at heights about half a scale height above perigee for both Explorer 19 (1963-53A) and Explorer 24 (1964-76A), which were the two satellites used in Ref.15. Even if the density bulge is genuinely in the winter hemisphere in the height range 600-750 km during 1964 and 1965, it will probably revert to the summer hemisphere as solar activity increases and atomic oxygen becomes increasingly important in this height band.

5 CONCLUSIONS

A comparison of the densities obtained from Echo 2 and Calsphere 1 during 1965 has confirmed that the average electric drag acting on Echo 2 is small, being of order 10% at most.

The secular acceleration of Calsphere 1 has also confirmed the finding of Ref.1 that there is a large semi-annual variation in air density in the region of 1100 km, for conditions of low solar activity. The large magnitude cannot be explained entirely on the basis of diffusion models and a semi-annual variation in exospheric temperature. It is probable that the large magnitude is partially attributable to variations in the boundary conditions at the level where diffusive equilibrium commences, viz. between 100 and 120 km. Helium is a major constituent in the lower exosphere, i.e. at heights between 500 and 1200 km, and its concentration in this region is particularly sensitive to the height of the turbopause.

Variations in the boundary conditions may also explain the location of the diurnal bulge in the winter hemisphere at heights of 600-700 km during conditions of low solar activity.

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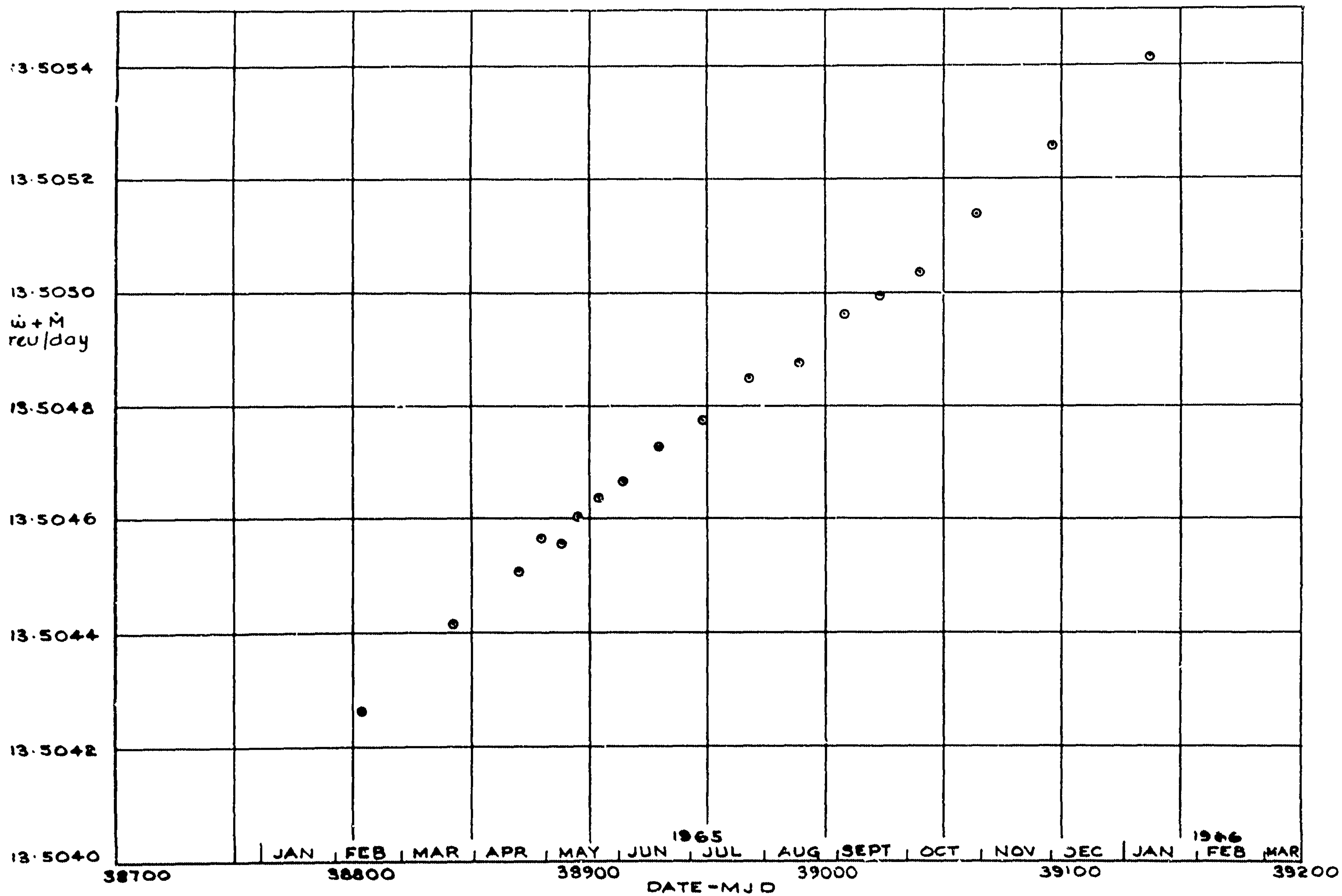

FIG. I. VARIATION OF $\dot{\omega}+\dot{M}$ FOR CALSPHERE I

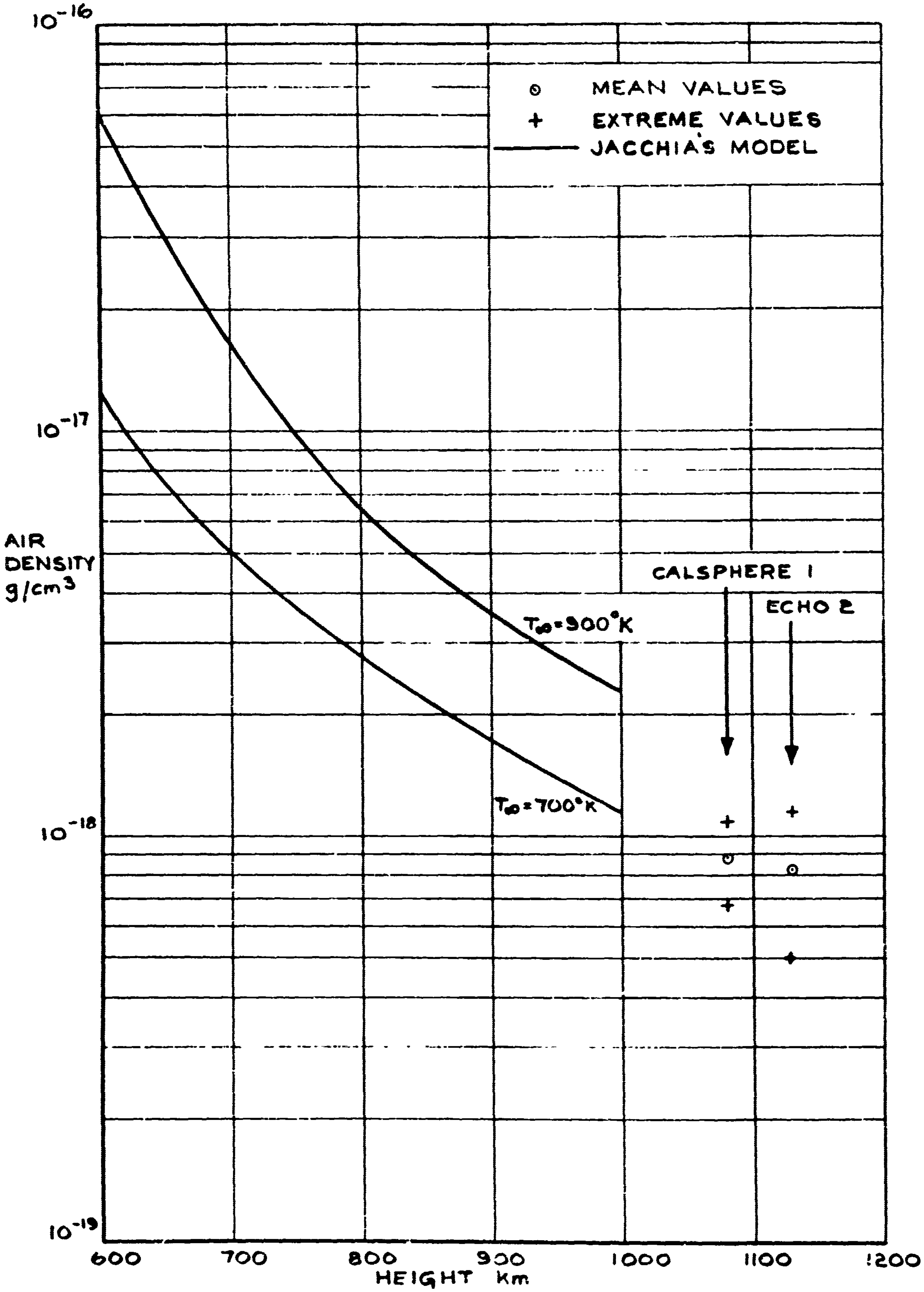

FIG. 2. VALUES OF AIR DENSITY IN 1965